

**LLC RESONANT CONVERTER TOPOLOGIES  
FOR PLUG-IN ELECTRIC VEHICLE  
BATTERY CHARGING**

**MUHAMMAD IMRAN SHAHZAD**

**UNIVERSITY SAINS MALAYSIA**

**2017**

**LLC RESONANT CONVERTER TOPOLOGIES FOR PLUG-IN ELECTRIC  
VEHICLE BATTERY CHARGING**

**by**

**MUHAMMAD IMRAN SHAHZAD**

**Thesis submitted in fulfillment of the requirements  
for the degree of  
Doctor of Philosophy**

**June 2017**

## ACKNOWLEDGEMENTS

Extremes of my regards from the depth of my heart to Almighty Allah ﷻ, The compassionate, The merciful, Who gave health, thoughts, affectionate parents, talented teachers, helping friends, and opportunity to contribute the vast body of knowledge and I offer praises to Holly Prophet Muhammad ﷺ Whose incomparable life is the glorious model for humanity, and Who is a mercy for all mankind.

I am highly grateful and my sincerest thanks and appreciation to my supervisor, Dr. Shahid Iqbal for his guidance, support, encouragement, and dynamic supervision throughout this research. His personal interest, valuable suggestions, most cooperative and affectionate behavior, constructive and thoughtful criticism, deep knowledge of circuits, and pin point solutions to the problems has resulted in timely completion of my research work. His enthusiasm, ambition and passion towards carrier will continue to inspire me in the rest of my life. I am also very thankful to my co-supervisor Assoc. Prof. Dr. Soib Taib for his valuable suggestions and discussions about my research work during the entire duration of my studies at Universiti Sains Malaysia.

I am very thankful to School of Electrical and Electronics Engineering, University Sains Malaysia, for providing necessary lab facilities for experimental testing of circuits during the entire research work. Special thanks to PCB lab technicians Mr. Elias Zainudin, and Mr. Kamarulzaman Abu bakar for fabrication of PCBs for my experimental prototypes. I am also very grateful to components stokist Mr. Amir Hamid, Research Officer Mr. Nazir Abdullah, Assistant Engineers Mr. Hairul Nizam Abdul Rahman, Mr. Ahmad Shauki Noor, and Mr. Jamaluddin Che Amat, in power electronics labs for their technical guidance to handle the instruments during experimental validation of the performance of my implemented circuits.

I extend my regards and sincerest thanks to all my group fellows especially Muhammad Faizal Abdullah, Adrian Tan Soon Theam, Nur Azura Samsudin, and Nurul Asikin Binti Zawawi for their cooperation, help, and technical discussions during my research work. I am also thankful to my post graduate room fellow Tiang Tow Liang for his nice company and general discussions during my study.

I am also very thankful to my Pakistani friends, Zia-ud-din, Abdur-ur-Rehman, Ubaidullah, Ashar Ahmad, Gul Muneer Ujjan, Faheemullah Jaan, Indian friends, Mussavir, Ayub, Kumar, Nishat Akhtar and Arabic friends Abdul Malik, Hisham, Adnan Haider, Hisham Ahmad, and favorite to all Tariq Adnan from USM Engineering campus for their nice company, support, and encouragement.

My deepest love and gratitude to my loving and affectionate father, my mother (late), my wife and son Ali Hassan, cute little Muhammad Mustafa, brothers and their wives, sister and her family, cousins, my loving grandfather, and grandmother (late) who always prayed for my health and brilliant future. Their concern, sincere support, and love can never be paid back. My special thanks and regards to my elder brother Hafeezullah Warraich and his family, my uncles and their families, who always supported and helped me in every situation.

Finally I would like to acknowledge the Universiti Sains Malaysia for providing funding for my research work through Research University Grant (RUI) No. 1001/PELECT/814207. I am very thankful to the University for providing funds for conferences and components required in experimental prototypes during the entire duration of my research, and for making this research possible.

## TABLE OF CONTENTS

	<b>Page</b>
<b>ACKNOWLEDGEMENTS</b>	ii
<b>TABLE OF CONTENTS</b>	iv
<b>LIST OF FIGURES</b>	xiii
<b>LIST OF PLATES</b>	xxiii
<b>LIST OF SYMBOLS</b>	xxiv
<b>LIST OF ABBREVIATIONS</b>	xxvii
<b>ABSTRAK</b>	xxix
<b>ABSTRACT</b>	xxxix
<b>CHAPTER ONE : INTRODUCTION</b>	
1.1 Background	1
1.2 Power Architecture of PEV and Power Conversion Interfaces	3
1.3 Characteristics of Lithium-ion Battery and Charging Profile	5
1.3.1 Two Stage On-board PEV Battery Charger	7
1.3.2 Charging Power Levels	8
1.4 Problem Statement	9
1.5 Research Objectives	10
1.6 Thesis Contributions	10
1.7 Thesis Outlines	13
<b>CHAPTER TWO : LITERATURE REVIEW</b>	
2.1 Introduction	15

2.2	Typical Two Stage on-board PEV Battery Charger	16
2.3	Power Factor Correction Stage with AC-DC Converter	17
2.3.1	PFC Boost Converter	19
2.3.2	Hysteresis Band Control of Boost Inductor Current	21
2.4	Front-end AC/DC PFC Topologies	23
2.4.1	Boost PFC Converter	23
2.4.2	Bridgeless Boost PFC Converter	24
2.4.3	Interleaved Boost PFC Converter	25
2.5	Second Stage Isolated DC/DC Converters	26
2.6	Isolated Full-bridge Converters with Pulse Width Modulation	26
2.6.1	Full-bridge Isolated PWM Buck converter	26
2.6.2	PWM ZVS and Phase-shifted Full-bridge Converter	27
2.7	Resonant Converter Topologies	30
2.7.1	Series Resonant Converter	33
2.7.2	Parallel Resonant Converter	36
2.7.3	Series-Parallel Resonant Converter	38
2.7.4	LLC Resonant Converter	41
2.8	Comparison of Resonant Converters for PEV Battery Charging	44
2.8.1	Series Resonant Converter for PEV Battery Charging	48
2.8.2	Parallel Resonant Converter for PEV Battery Charging	49
2.8.3	Series-Parallel Resonant Converter for PEV Battery Charging	51

2.8.4	LLC Series Resonant Converter for PEV Battery Charging	53
2.9	State of the Arts Battery Charging Solutions	55
2.9.1	Conventional Series Resonant Converter Topologies	55
2.9.2	Half-bridge LLC Resonant Converter Topologies	56
2.9.3	Full-bridge LLC Resonant Converter Topologies	57
2.9.4	Control Strategies for Recovery Region of Battery	60
2.9.4(a)	Burst Mode Control	60
2.9.4(b)	Variable DC-Link Approach	61
2.9.4(c)	Hybrid Control Scheme	62
2.9.4(d)	Higher Order Converter using Wide Frequency Variation	62
2.9.4(e)	Variable Structure Rectifier Approach	62
2.10	Efficiency Comparison of Topologies for Battery Charging	63
2.11	Summary	64
 <b>CHAPTER THREE : METHODOLOGY</b>		
3.1	Introduction	65
3.2	Double LLC Tank Resonant Converter	66
3.2.1	Analysis of Steady-State Operation	68
3.2.2	Analysis of Gain Characteristics of Converter	76
3.2.3	Effect of Inductance Ratio and Quality Factor on Voltage Gain	80
3.3	Double LLC Tank Resonant Converter with Hybrid-Rectifier	81

3.3.1	Analysis of Steady State Operation	83
3.3.2	Gain Characteristics of Converter	84
3.4	Hybrid Bridge LLC Resonant Converter	88
3.4.1	Analysis of Steady State Operation	89
3.4.1(a)	Full-Bridge Mode of Operation (FBBR)	91
3.4.1(b)	Half-Bridge Mode of Operation (HBBR)	97
3.4.2	Gain Analysis of Hybrid-Bridge LLC Resonant Converter	102
3.5	Hybrid-bridge LLC Resonant Converter with Hybrid-Rectifie	105
3.5.1	Analysis of Gain Characteristics	108
3.6	Interleaved LLC Converter with Voltage doubler Rectifiers	111
3.6.1	Analysis of Steady State Operation	113
3.6.1(a)	Independent Mode of Operation	113
3.6.1(b)	Simultaneous Mode of Operation	117
3.6.2	Analysis of Gain Characteristics	122
3.7	Comparison of Proposed Topologies	126
3.8	Summary	127
<b>CHAPTER FOUR : DESIGN AND IMPLEMENTATION</b>		
4.1	Introduction	128
4.2	General Design Procedure of LLC Resonant Converter Topologies	128
4.3	Double LLC Tank Resonant Converter	130
4.3.1	Design Considerations and Operation of Converter	130



4.3.2	Implementation Procedure	134
4.3.2(a)	Selection of Switches for Implementation of switching Network	135
4.3.2(b)	Resonant Tank Component Selection and Transformer Structure	136
4.3.2(c)	Selection of Bridge Rectifier Diodes and Filter Capacitor	138
4.3.2(d)	Implementation of Experimental Prototype	138
4.4	Double LLC Tank Resonant Converter with Hybrid-Rectifier	139
4.4.1	Design Considerations and Operation of Converter	140
4.4.2	Implementation procedure	144
4.5	Hybrid-bridge LLC Resonant Converter	146
4.5.1	Design Considerations and Operation of Converter	147
4.5.2	Implementation Procedure	151
4.5.3	Implementation of Experimental prototype	152
4.5.3(a)	Implementation of Hybrid-bridge Switching Network	153
4.5.3(b)	Transformer Structure	154
4.5.4	Experimental Prototype of Converter	155
4.6	Hybrid-bridge LLC Resonant Converter with Hybrid-rectifier	156
4.6.1	Design Considerations and Operation of Converter	156
4.6.2	Simulation Model and Experimental Prototype	161
4.7	Interleaved LLC Resonant Converter with Voltage doubler Rectifiers	162

4.7.1	Design Considerations and Operation of Converter	163
4.7.2	Simulation Model and Experimental Prototype	168
4.8	Frequency Controller and Gate Driver	170
4.9	Implementation of Equivalent High Power Battery Load	174
4.10	Summary	175
<b>CHAPTER FIVE : RESULTS AND DISCUSSIONS</b>		
5.1	Introduction	176
5.2	Simulation and Experimental Results of Double LLC Tank Resonant Converter	176
5.3	Simulation and Experimental Results of Double LLC Tank Resonant Converter with Hybrid-Rectifier	183
5.3.1	Deeply Depleted Battery Charging	185
5.3.2	Normally Depleted Battery Charging	188
5.4	Simulation and Experimental Results of Hybrid-Bridge LLC Converter	196
5.5	Results of Hybrid-Bridge LLC Resonant Converter with Hybrid-Rectifier	204
5.5.1	Deeply Depleted Battery Charging using HBBR and FBBR Modes	205
5.5.2	Depleted Battery Charging using FBVD Mode of Operation	208
5.6	Simulation and Experimental Results of Interleaved LLC Resonant Converter with Voltage Doubler Rectifiers	214

5.6.1	Deeply Depleted Battery Charging	215
5.6.1(a)	Method-1: Independent Mode of Operation	215
5.6.1(b)	Method-2: Simultaneous Mode of Operation	217
5.6.2	Depleted Battery Charging	221
5.7	Efficiency Comparison of Proposed Topologies	227
5.8	Summary	228
<b>CHAPTER SIX : CONCLUSION</b>		
6.1	Conclusion	229
6.2	Future Work	233
<b>REFERENCES</b>		234

## **LIST OF PUBLICATIONS**

## LIST OF TABLES

		<b>Page</b>
Table 1.1	EVs AC charging power levels [4, 19].	9
Table 2.1	Key point in the charging profile of PEV battery pack [41].	46
Table 2.2	Parameters of four resonant converter topologies [41].	47
Table 2.3	Performance comparison of resonant converters in PEV battery charging.	55
Table 2.4	Efficiency comparison of various LLC resonant converter topologies for battery charging at peak output power.	63
Table 3.1	Comparison between proposed topologies in term of dc gain and $R_{ac}$ .	126
Table 4.1	Specifications and parameters of double LLC tank resonant converter.	132
Table 4.2	Key operating point of double LLC tank resonant converter.	132
Table 4.3	Measured stress on components from simulation at maximum power.	134
Table 4.4	Used components in experimental prototype with ratings.	138
Table 4.5	Specifications and calculated parameters of double LLC tank resonant converter.	142
Table 4.6	Key operating points of the double LLC tank resonant converter.	142
Table 4.7	Measured stress on components form simulation at maximum power.	145
Table 4.8	Specifications and calculated parameters of converter.	149
Table 4.9	Measured peak currents and voltages across components from simulation.	151
Table 4.10	Parameters of hybrid-bridge LLC converter with hybrid-rectifier.	158

Table 4.11	Key operating points for hybrid-bridge LLC converter with hybrid-rectifier.	159
Table 4.12	Components stress measured from simulation of converter at maximum power.	161
Table 4.13	Design specifications and calculated parameters of HB interleaved converter.	165
Table 4.14	Key operating points for hybrid-bridge LLC converter with hybrid-rectifier.	165
Table 4.15	Components stress measured from simulation of converter at maximum power.	168
Table 5.1	Operating modes of converter and corresponding key operating points.	184
Table 5.2	Operating modes of proposed converter with corresponding key operating points.	197
Table 5.3	Operating modes of proposed converter with corresponding key operating points.	204
Table 5.4	Key operating points and corresponding modes of operation of converter.	214
Table 5.5	Efficiency comparison between proposed topologies at key operating points.	228

## LIST OF FIGURES

		<b>Page</b>
Figure 1.1	Projected annual PEV sales in top five states in the United States: 2013-2022 [5].	2
Figure 1.2	Li-ion pricing and energy density (1991-2006) [8].	3
Figure 1.3	General power architecture of an electric vehicle [9].	4
Figure 1.4	Charging profile of a Li-ion battery cell [16].	6
Figure 1.5	Charging current and voltage for 1.5 kW battery pack in one cycle using CC-CV method and key operating points in one charging cycle.	7
Figure 1.6	Power architecture of a two-stage on-board PEV battery charger [18].	8
Figure 2.1	Power architecture of on-board battery charger [30].	16
Figure 2.2	AC-DC converter at PFC stage of battery charger [34].	17
Figure 2.3	Line input voltage, line input current and rectifier output voltage in conventional AC-DC converters [35, 36].	18
Figure 2.4	PFC boost converter [38].	19
Figure 2.5	Inductor current confined within hysteresis band for half cycle of input voltage. (a) Fixed width hysteresis band, (b) varying width band.	21
Figure 2.6	Inductor current confined within hysteresis band and gate pulses of the boost converter switch.	22
Figure 2.7	Single phase boost PFC converter [9].	23
Figure 2.8	Bridgeless boost PFC converter [34, 38, 40].	25
Figure 2.9	Interleaved boost PFC converter [40].	25
Figure 2.10	Isolated PWM buck converter [9].	27
Figure 2.11	ZVS PWM full-bridge converter [28, 43, 44].	28

Figure 2.12	Phase-shifted full-bridge converter [47].	29
Figure 2.13	Typical configuration of resonant DC-DC converters.	30
Figure 2.14	Switching circuit configurations, (a) Half-bridge, (b) Full-bridge.	31
Figure 2.15	Resonant tank circuits, (a) series, (b) parallel, (c) series-parallel, (d) LLC.	32
Figure 2.16	Rectifier and filter capacitor, (a) Full-bridge, (b) Voltage doubler.	33
Figure 2.17	Half-bridge series resonant converter, (a) Circuit diagram, (b) AC equivalent circuit [64, 65].	34
Figure 2.18	DC gain characteristics of series resonant converter.	35
Figure 2.19	Half-bridge parallel resonant converter, (a) Circuit diagram, (b) AC equivalent circuit [64, 65].	37
Figure 2.20	DC gain characteristics of parallel resonant converter.	38
Figure 2.21	Half-bridge series-parallel resonant converter, (a) Circuit diagram, (b) AC equivalent circuit [64, 65].	39
Figure 2.22	DC gain characteristics of series-parallel resonant converter.	40
Figure 2.23	Half-bridge LLC series resonant converter, (a) Circuit diagram, (b) AC equivalent circuit [64, 65].	42
Figure 2.24	DC gain characteristics of LLC series resonant converter.	43
Figure 2.25	Charging characteristics of single cell Li-ion battery [41].	45
Figure 2.26	Charging profile of 360 V Li-ion battery pack rated at 3.2 kW.	45
Figure 2.27	DC Voltage and current characteristics of SRC for PEV battery charging [41].	48
Figure 2.28	DC Voltage and current characteristics of PRC for PEV battery charging [41].	50
Figure 2.29	DC Voltage and current characteristics of SPRC for PEV battery charging [41].	52

Figure 2.30	DC Voltage and current characteristics of LLC for PEV battery charging [41].	54
Figure 2.31	Lead-acid battery charger using half-bridge LLC resonant converter [27].	56
Figure 2.32	Charging profile of 48 V lead-acid battery pack [29].	57
Figure 2.33	Full-bridge LLC series resonant converter [16, 18].	57
Figure 2.34	LLC converter with semiactive variable-structure rectifier (SA-VSR) [88].	59
Figure 2.35	Desired charging profile of 48 V lead acid battery [27, 85].	60
Figure 2.36	Charging range using VFFOT and FFVOT in burst mode [27, 85].	61
Figure 3.1	Double LLC tank resonant converter.	67
Figure 3.2	Key steady-state waveforms of proposed double LLC tank resonant converter.	69
Figure 3.3	Equivalent circuits for intervals 1-4 during first half switching cycle: (a) interval 1 ( $t_0-t_1$ ); (b) interval 2 ( $t_1-t_2$ ); (c) interval 3 ( $t_2-t_3$ ); (d) interval 4 ( $t_3-t_4$ ).	71
Figure 3.4	Equivalent circuits for intervals 5-8 during second half switching cycle: (e) interval 5 ( $t_4-t_5$ ), (f) interval 6 ( $t_5-t_6$ ), (g) interval 7 ( $t_6-t_7$ ), and (h) interval 8 ( $t_7-T+ t_0$ ).	72
Figure 3.5	AC equivalent circuit of upper resonant tank $R_{T1}$ .	77
Figure 3.6	Plot of gain vs normalized frequency $f_n$ for $k = 5$ and different values of $Q$ .	80
Figure 3.7	Plot of gain vs normalized frequency $f_n$ for $Q = 0.3$ and different values of $k$ .	81
Figure 3.8	Double LLC tank resonant converter with hybrid-rectifier.	82
Figure 3.9	AC equivalent circuit of proposed converter.	85
Figure 3.10	Hybrid-bridge LLC series resonant converter.	88



Figure 3.11.	Modes of operation of converter (a) Full-bridge (b) Half-bridge.	90
Figure 3.12	Logic Circuit for half-bridge to full-bridge transition of LLC converter.	90
Figure 3.13	Key steady state waveforms of hybrid-bridge LLC resonant converter in full-bridge operating mode.	92
Figure 3.14	Equivalent circuits of intervals for first half cycle of FBBR mode of operation: (a) interval 1 ( $t_0-t_1$ ); (b) interval 2 ( $t_1-t_2$ ); (c) interval 3 ( $t_2-t_3$ ); (d) interval 4 ( $t_3-t_4$ ).	94
Figure 3.15	Equivalent circuits of intervals for second half cycle of FBBR mode of operation: (e) interval 5 ( $t_4-t_5$ ), (f) interval 6 ( $t_5-t_6$ ), (g) interval 7 ( $t_6-t_7$ ), and (h) interval 8 ( $t_7-T+ t_0$ ).	95
Figure 3.16	Key steady state waveforms of hybrid-bridge LLC resonant converter in HBBR operating mode.	98
Figure 3.17	Equivalent circuits of first four intervals for HBBR mode: (a) interval 1 ( $t_0-t_1$ ); (b) interval 2 ( $t_1-t_2$ ); (c) interval 3 ( $t_2-t_3$ ); (d) interval 4 ( $t_3-t_4$ ).	100
Figure 3.18	Derivation process of AC equivalent circuit, (a) replacement of rectifier with AC load (b) AC equivalent circuit of converter.	104
Figure 3.19	Proposed hybrid-bridge LLC resonant converter with hybrid-rectifier.	106
Figure 3.20	FBVD mode of operation of proposed converter.	106
Figure 3.21	Derivation process of AC equivalent circuit, (a) replacement of rectifier with AC load (b) AC equivalent circuit of converter.	110
Figure 3.22	Interleaved LLC converter with voltage doubler rectifiers.	112
Figure 3.23	Key steady state waveforms of proposed interleaved converter for independent operational mode.	114
Figure 3.24	Equivalent circuits for first four intervals of interleaved converter operating in independent mode: (a) interval 1 ( $t_0-t_1$ ); (b) interval 2 ( $t_1-t_2$ ); (c) interval 3 ( $t_2-t_3$ ); (d) interval 4 ( $t_3-t_4$ ).	116
Figure 3.25	Key steady state waveforms of proposed interleaved converter for simultaneous operational mode.	118

Figure 3.26	Equivalent circuits for first four intervals of interleaved converter operating in simultaneous mode: (a) interval 1 ( $t_0-t_1$ ); (b) interval 2 ( $t_1-t_2$ ); (c) interval 3 ( $t_2-t_3$ ); (d) interval 4 ( $t_3-t_4$ ).	119
Figure 3.27	Derivation process of AC equivalent circuit, (a) circuit diagram of converter-1 (b) converter-1 with AC load (c) AC equivalent circuit of converter-1.	124
Figure 4.1	Peak gain of designed double LLC tank resonant converter.	131
Figure 4.2	Output voltage versus switching frequency curves for key operating points of converter with frequency variation range for CC and CV charging.	133
Figure 4.3	Flow chart of the converter for one battery charging cycle.	133
Figure 4.4	Simulation Model of double LLC tank resonant converter.	134
Figure 4.5	Half-bridge configuration of switching circuit for double LLC tank converter.	135
Figure 4.6	Transformer structure with center-tapped primary windings.	136
Figure 4.7	Peak gain of curve of double LLC tank resonant with hybrid-rectifier.	140
Figure 4.8	Output voltage versus switching frequency curves of converter for key operating points with operating ranges for different charging modes.	142
Figure 4.9	Flow chart of converter operation for one charging cycle.	144
Figure 4.10	MATLAB Simulation model of double LLC tank resonant converter with hybrid-rectifier.	145
Figure 4.11	Peak gain curve of hybrid-bridge LLC resonant converter.	148
Figure 4.12	Output voltage versus switching frequency curves of converter for key operating points with operating frequency ranges for different charging modes of battery.	149
Figure 4.13	Flow chart of converter operation for one complete charging cycle.	151
Figure 4.14	MATLAB Simulation Model of hybrid-bridge LLC resonant converter.	152

Figure 4.15	Hybrid-bridge configuration of switching circuit.	153
Figure 4.16	Transformer structure with adjacent primary and secondary windings.	154
Figure 4.17	Gain curves of designed converter for HBBR, FBBR and FBVD modes and the mode transitions.	157
Figure 4.18	Output voltage versus switching frequency curve for $Q$ values corresponding to key operating points for three mode of hybrid-bridge LLC converter with hybrid-rectifier.	159
Figure 4.19	Flow chart of converter operation for one complete charging cycle.	160
Figure 4.20	Simulation Model of hybrid-bridge LLC converter with hybrid-rectifier.	161
Figure 4.21	Gain curve of half-bridge LLC converter with voltage doubler.	164
Figure 4.22	Output voltage versus switching frequency curve for $Q$ values corresponding to key operating points of converter for two operating modes of interleaved converter.	166
Figure 4.23	Flow chart of converter operation for one complete charging cycle.	168
Figure 4.24	Simulation model of Interleaved LLC converter with voltage doubler rectifiers.	169
Figure 4.25	Schematic of frequency controller using UCC2895N resonant mode controller to generate switching pulses [90].	170
Figure 4.26	Dead-time and switching frequency control of UCC2895N, (a) Dead-time control with delay resistance at DELAB, (b) Oscillator frequency control with CT and RT [90].	171
Figure 4.27	Schematic of gate driver for isolation of controller from converter.	171
Figure 4.28	(a) Schematic of load bank and Photographs of (b) 3 kW load bank, (c) 1.5 kW $47\Omega$ resistor, and (d) 50W low power load resistor.	174

Figure 5.1	Operating waveforms of double LLC tank resonant converter at key operating point C ( $V_0 = 250$ V and $I_0 = 3.57$ A): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	178
Figure 5.2	Operating waveforms of double LLC tank resonant converter at a point between key points C and D with $V_0 = 320$ V and $I_0 = 3.57$ A: (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	179
Figure 5.3	Operating waveforms of double LLC tank resonant converter at key operating point D ( $V_0 = 420$ V and $I_0 = 3.57$ A): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	180
Figure 5.4	Operating waveforms of double LLC tank resonant converter at key operating point E ( $V_0 = 420$ V and $I_0 = 0.255$ A): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	181
Figure 5.5	Experimental waveforms of input voltage $V_{in}$ , output voltage $V_0$ , and output current $I_0$ at key operating points (a) C, (b) at 320V between C and D, (c) D, (d) and E.	182
Figure 5.6	Measured efficiency of converter for (a) CC charging (b) CV charging.	183
Figure 5.7	Operating waveforms of double LLC tank resonant converter with hybrid-rectifier at key point A ( $V_0 = 100$ V and $I_0 = 0.357$ A): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	186
Figure 5.8	Operating waveforms of double LLC tank resonant converter with hybrid-rectifier at key point B ( $V_0 = 250$ V and $I_0 = 0.357$ A): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	187
Figure 5.9	Operating waveforms of double LLC tank resonant converter with hybrid-rectifier at key point C ( $V_0 = 250$ V and $I_0 = 3.57$ A): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	190
Figure 5.10	Operating waveforms of double LLC tank resonant converter with hybrid-rectifier at key point D ( $V_0 = 420$ V and $I_0 = 3.57$ A): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	191

Figure 5.11	Operating waveforms of double LLC tank resonant converter hybrid-rectifier at key point E ( $V_0 = 420\text{V}$ and $I_0 = 0.255\text{A}$ ): (a)–(d) are simulation waveforms and (e)–(h) are experimental waveforms.	192
Figure 5.12	Effect of mismatches in the value of resonant components on resonant currents for operation near resonance frequency $f_{r1}$ : (a) resonant currents for the case of mismatching parameters (b) resonant currents for the matching parameters case in experimental prototype.	193
Figure 5.13	Experimental waveforms of input voltage $V_{in}$ , output voltage $V_0$ , and output current $I_0$ at key operating points (a) A, (b) B, (c) C, (d) D, (e) and E.	194
Figure 5.14	Measured efficiency of converter (a) CC charging with both 2LLC-HBBR and 2LLC-HBVD operating modes (b) CV charging with 2LLC-HBVD mode.	195
Figure 5.15	Waveforms of hybrid-bridge LLC converter operation at key point A using HBBR mode with $V_0 = 100\text{V}$ and $I_0 = 0.357\text{A}$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	198
Figure 5.16	Waveforms of hybrid-bridge LLC converter operation at key point B using HBBR mode with $V_0 = 250\text{V}$ and $I_0 = 0.357\text{A}$ , (a) & (b) are simulation and (c) & (d) are experimental waveforms.	199
Figure 5.17	Waveforms of hybrid-bridge LLC converter operation at key point C using FBBR mode with $V_0 = 250\text{V}$ and $I_0 = 3.57\text{A}$ , (a) & (b) are simulation and (c) & (d) are experimental waveforms.	200
Figure 5.18	Waveforms of hybrid-bridge LLC converter operation at key point D using FBBR mode with $V_0 = 420\text{V}$ and $I_0 = 3.57\text{A}$ , (a) & (b) are simulation and (c) & (d) are experimental waveforms.	201
Figure 5.19	Waveforms of hybrid-bridge LLC converter operation at key point E using FBBR mode with $V_0 = 420\text{V}$ and $I_0 = 0.255\text{A}$ , (a) simulation and (b) are experimental waveforms.	201
Figure 5.20	Experimental waveforms of input voltage $V_{in}$ , output voltage $V_0$ , and output current $I_0$ at key operating points (a) A, (b) B, (c) C, (d) D, (e) and E.	202

Figure 5.21	Measured efficiency of hybrid-bridge LLC converter (a) CC charging with both HBBR and FBBR operating modes (b) CV charging with FBBR mode.	203
Figure 5.22	Waveforms of converter operation using HBBR mode at key operating point A- with $V_0 = 50V$ and $I_0 = 0.357A$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	205
Figure 5.23	Waveforms of converter operation using HBBR at key operating point A+ with $V_0 = 125V$ and $I_0 = 0.357A$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	206
Figure 5.24	Waveforms of converter operation using FBBR mode at key operating point B- with $V_0 = 125V$ and $I_0 = 0.357A$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	207
Figure 5.25	Waveforms of converter operation using FBBR mode at key operating point B with $V_0 = 250V$ and $I_0 = 0.357A$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	208
Figure 5.26	Waveforms of converter operation using FBVD mode at key operating point C with $V_0 = 250V$ and $I_0 = 3.57A$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	209
Figure 5.27	Waveforms of converter operation using FBVD mode at key operating point D with $V_0 = 420V$ and $I_0 = 3.57A$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	210
Figure 5.28	Waveforms of converter operation using FBVD mode at key operating point E with $V_0 = 420V$ and $I_0 = 0.255A$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	211
Figure 5.29	Experimental waveforms of input voltage $V_{in}$ , output voltage $V_0$ , and output current $I_0$ at key operating points (a) A-, (b) A+, (c) B-, (d) B, (e) C, (f) D, (g) and E.	212
Figure 5.30	Measured efficiency of converter (a) for CC charging of deeply depleted battery in HBBR and FBBR mode and that of depleted battery in FBVD mode (b) for CV charging in FBVD mode.	213

Figure 5.31	Waveforms of converter operation using independent operation at key point A-HB with $V_o = 50\text{V}$ and $I_o = 0.357\text{A}$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	216
Figure 5.32	Waveforms of converter operation using independent operation at key point A <sub>HB</sub> with $V_o = 100\text{V}$ and $I_o = 0.357\text{A}$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	216
Figure 5.33	Waveforms of converter operation using independent operation at key point B <sub>HB</sub> with $V_o = 250\text{V}$ and $I_o = 0.357\text{A}$ , (a) & (b) are simulation waveforms and (c) & (d) are experimental waveforms.	217
Figure 5.34	Waveforms of converter operation using simultaneous operation at key point A with $V_o = 100\text{V}$ and $I_o = 0.357\text{A}$ , (a)–(c) are simulation waveforms and (d)–(f) are experimental waveforms.	218
Figure 5.35	Waveforms of converter operation using simultaneous operation at key point B with $V_o = 250\text{V}$ and $I_o = 0.357\text{A}$ , (a)–(c) are simulation waveforms and (d)–(f) are experimental waveforms.	219
Figure 5.36	Waveforms of converter operation in simultaneous mode at key point C with $V_o = 250\text{V}$ and $I_o = 3.57\text{A}$ , (a)–(c) are simulation waveforms and (d)–(f) are experimental waveforms.	222
Figure 5.37	Waveforms of converter operation in simultaneous mode at key point D with $V_o = 420\text{V}$ and $I_o = 3.57\text{A}$ , (a)–(c) are simulation waveforms and (d)–(f) are experimental waveforms.	223
Figure 5.38	Waveforms of converter operation in simultaneous mode at key point E with $V_o = 420\text{V}$ and $I_o = 0.255\text{A}$ , (a)–(c) are simulation waveforms and (d)–(f) are experimental waveforms.	224
Figure 5.39	Experimental waveforms of input voltage $V_{in}$ , output voltage $V_o$ , and output current $I_o$ at key operating points (a) A-HB, (b) A <sub>HB</sub> , (c) B <sub>HB</sub> , (d) A, (e) B, (f) C, (g) D, (h) and E.	225
Figure 5.40	Measured efficiency of converter (a) for CC charging of deeply depleted battery with independent mode and simultaneous mode, and for CC charging of depleted mode in simultaneous mode (b) for CV charging with simultaneous mode.	226

## LIST OF PLATES

		<b>Page</b>
Plate 4.1	Implemented experimental prototype of double LLC tank resonant converter.	139
Plate 4.2	Experimental prototype of double LLC tank resonant converter with hybrid-rectifier.	146
Plate 4.3	HB to FB transition circuit in hybrid-bridge.	154
Plate 4.4	Experimental Prototype of dual-bridge LLC converter.	155
Plate 4.5	Experimental prototype of hybrid-bridge LLC converter with hybrid-rectifier.	162
Plate 4.6	Experimental prototype of interleaved LLC converter with voltage doubler rectifiers.	169
Plate 4.7	Implemented frequency controller and gate driver.	173